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THE *IN VIVO* DYNAMIC MATERIAL PROPERTIES OF THE CANINE SPINAL CORD: A FEASIBILITY STUDY

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A study was completed which showed the feasibility of determining the *in vivo* dynamic material properties of the spinal cord in mongrel dogs. In the initial phase, sinusoidal pressure waves were induced on a fluid-filled thin-walled penrose surgical drainage tube and the wave front was monitored by two micropressure transducers. The wave speed obtained from these measurements was inserted into the Moens-Korteweg relation to determine the Young's modulus for the penrose tubing. The value obtained for the modulus was in excellent agreement

with values cited in the literature. In the second phase, a portion of the spinal cord of three dogs was exposed by a laminectomy and then the cord subjected to an identical wave propagation method of procedure as determined in the initial phase. It was important to block the spinal cord jerk reflex by a local anesthetic, Xylocaine®, distal to the test section of the cord before the start of the experiment. Thus, the surgical tools, electro-mechanical equipment and accessories, and the method of procedure required for the successful determination of some of the *in vivo* dynamic material properties of the spinal cord of dogs was established.

SUMMARY

A study was completed which showed the feasibility of determining the *in vivo* dynamic material properties of the spinal cord in mongrel dogs. In the initial phase, sinusoidal pressure waves were induced on a fluid-filled thin-walled penrose surgical drainage tube and the wave front was monitored by two micropressure transducers. The wave speed obtained from these measurements was inserted into the Moens-Korteweg relation to determine the Young's modulus for the penrose tubing. The value obtained for the modulus was in excellent agreement with values cited in the literature. In the second phase, a portion of the spinal cord of three dogs was exposed by a laminectomy and then the cord subjected to an identical wave propagation method of procedure as determined in the initial phase. It was important to block the spinal cord jerk reflex by a local anesthetic, Xylocaine®, distal to the test section of the cord before the start of the experiment. Thus, the surgical tools, electro-mechanical equipment and accessories, and the method of procedure required for the successful determination of some of the *in vivo* dynamic material properties of the spinal cord of dogs was established.

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ROBERT W. BAILEY
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Commander

PREFACE

This report was submitted to the US Army Aeromedical Research Laboratory in fulfillment of Contract No. DAMD 17-74-G-9384.

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INTRODUCTION

Spinal cord injuries, particularly those which result in paraplegia and quadriplegia, present an economic problem of staggering magnitude. The chief cause of these injuries are automobile, industrial and sports accidents. In addition, war casualties are also a major contributor for these traumatic injuries.

The greatest deficit in physiopathological studies is the lack of investigations linking the mechanics of the input trauma to the sequence of physiopathologic responses. A fairly large effort on the material properties of the vertebrae and discs has been supported by such Federal agencies as the Departments of Defense and Transportation as well as the National Institutes of Health. However, the *dynamic, in vivo* material properties of the spinal cord itself is practically nonexistent. Without this class of data, the physiopathologic understanding would at best be qualitative and thus incomplete. The purpose of the present report is to detail a feasibility study towards filling this gap in our quantitative knowledge and understanding of the response of the spinal cord under dynamic loads. Since the central nervous system (CNS), consisting of the cortex, brainstem, spinal cord and cauda equina, is a closed, integral functional unit, the material properties determined from the dura-invested brain tissue at the spinal cord level should also shed much light on the material behavior for the rest of the CNS.

BRIEF REVIEW OF PREVIOUS WORK

Extensive investigations have been reported on wave propagation characteristics on fluid filled elastic/viscoelastic tubes mainly as a model for blood flow in the circulatory system. Some typical publications are those of Womersley (1957), Atabek (1968) and Maxwell and Anliker (1968). The theory of wave propagation has also been successfully applied in *in vivo* experimental analysis of the behavior of the blood vessels in dogs and a detailed review is found in Anliker (1972).

The dura mater has been tested *in vitro*. McElhaney *et al.* (1972) reported a mean Young's modulus of approximately 6000 psi under quasi-static conditions and 8800 psi at a strain rate of 6.66 sec^{-1}. The viscoelastic description of the brain material, which is also contained in the spinal cord, has been achieved through *in vitro* testing. The two quantities of interest are the complex bulk modulus and the complex shear modulus. There is general consensus, see McElhaney *et al.* (1972), that the bulk modulus is about 300,000 psi and independent of frequency; i.e., the brain has an elastic response to hydrostatic loading. Fallenstein *et al.* (1969) subjected rectangular specimens of brain to a sinusoidally varying shear stress and measured the resulting strain. They obtained a real part in the range of 0.09 to 0.16 psi and a loss tangent (the ratio of the imaginary to the real part) from 0.40 to 0.55 in the frequency range of 9-10 Hz. Shuck and Advani (1972) imposed a uniform steady state angular displacement on one base of a brain-filled cylinder and measured the torque magnitude and phase transmitted through the cylinder. The theoretical analysis of the experiment allowed the computation of the imaginary and real parts of the complex shear modulus to be calculated. The test was conducted at a frequency range of 1-350 Hz. The values reported by Shuck and Advani (1972) differed from Fallenstein et al. (1969) by an order of magnitude. It is fairly easy to show that for an impact of several milliseconds duration, it is necessary to know the shear modulus function over the frequency range of 0-2200 Hz.

While the in vitro work cited above is important and necessary, one cannot infer that their combination must ipso facto be their in vivo behavior. Three factors can contribute to the discrepancy: (i) The spinal cord is axially tethered, see Breig (1960); (ii) The brain matter and the dura mater are both viscoelastic; and, (iii) The soft tissue pressure on the spinal cord from its surroundings. Thus, the need for in vivo experiments is clearly obvious.

THEORETICAL BACKGROUND OF THE PRESENT STUDY

With the values obtained from the in vitro experiments mentioned above, the spinal cord can be considered as a thin-walled elastic membraneous tube filled with a viscous incompressible fluid. The Wall of the dura mater is assumed to have isotropic, homogeneous and viscoelastic properties. Classical wave propagation theory and experiment have been applied to determine its material properties - as has been shown by Anliker (1972). Three types of waves are present when such a system is disturbed as given below:

$$c_p = (Eh/2\rho_f a)^{\frac{1}{2}}, \tag{1}$$

where E is the Young's modulus in the circumferential direction of the vessel wall, h is the wall thickness of the vessel, ρ_f is the density of the fluid and a is the radius of the tube.

$$c_a = [E/\rho_s(1-\nu^2)]^{\frac{1}{2}}, \tag{2}$$

where ρ_s is the density of the wall and ν, its Poisson's ratio.

$$c_t = (G/\rho_s)^{\frac{1}{2}} \tag{3}$$

where G is the shear modulus of the wall. These waves are referred to as the pressure, axial and torsional waves according to their predominant physical characteristics. The pressure waves are characterized by a strong interaction between the fluid contained within the tube and the tube wall whereas the axial and torsional waves exhibit very little fluid-membrane interaction. It has been shown by Anliker (1972) that it is possible to induce small transient signals in which one of the three waves is dominant and measures its phase velocity, dispersion and attenuation properties as a function of the applied frequencies. By selecting transient signals in the form of a finite train of sine waves, the need for Fourier transform computation is eliminated if the wall medium is mildly dispersive, i.e., the phase velocity is changed by a few percent when the frequency is changed by 10%. Since the Fourier spectrum of the input signal is dominated in proportion to the length of the train at the input frequency, the speed of the transient signal is a good approximation to the phase velocity at the given frequency.

The wave transmission characteristics described above have been extensively studied on fluid-filled latex rubber tubes by Klip et al. (1967). But, careful consideration must be given in applying the theory to physiological conditions in vivo. In physiological systems like blood vessels and the spinal cord, we would expect a wave velocity of the order of 5.0 to 10.0 m/sec and at a frequency of 1 Hz, the wave length will be of the order of 5.0 to 10.0 m which implies that within the period of each pulse, we can expect multiple reflections and distortions of the wave shape. These reflections make the determination of the phase velocities and attenuation a much more complicated task. Moreover, Maxwell and Anliker (1968) have shown that in blood vessels, pressure waves of high frequency and small amplitudes are dissipated primarily by the viscoelastic behavior of the wall. In the light of the above considerations, it is thus, preferable to perform the wave propagation studies in vivo at high frequencies in the order of 100 Hz. than at the lower frequencies. The assumption that the spinal cord consists of a viscoelastic membraneous tapered tube containing an inviscid and incompressible fluid is also justified if limited to high frequencies. Additionally, the material properties for the high strain rates encountered in trauma, correspond to precisely its high frequency response.

FEASIBILITY STUDY

A feasibility study was completed during the period of November, 1973 through June, 1974, in an attempt to determine the in vivo dynamic material properties of the spinal cord in mongrel dogs. This study was divided into two parts:

(i) Determine the transducing system and the associated electromechanical equipment required to induce and monitor the wave propagation characteristics of the spinal cord.

(ii) Establish the surgical procedure for the dogs as well as determining what additional surgical tools, equipment and accessories were necessary for the successful completion of the project.

Mechanical Wave Transmission in Thin Latex Tubing

To determine whether induced sinusoidal pressure waves on the spinal cord can be successfully monitored with pressure transducers pressed against the outer wall of the cord, initial experiments were performed on commercially available thin-walled penrose surgical drainage tubing (No. 912D3, Davol, Inc., Providence, Rhode Island). This tubing was made of amber latex rubber with a diameter of ½ inch and wall thickness to radius ratio of 0.05. On either side of the tubing, long rubber tubes were attached and filled with water maintained at a small hydrostatic pressure with a reservoir on one end of the tube. A long aluminum rod (1/8 in. dia.) was mounted on an electromagnetic (EM) shaker (Ling Electronics Model 203), which was driven by a sine wave generator connected to an audio amplifier (Dynakit Mark III). Two micro-pressure transducers (Kulite Model CQL-080-4) mounted on 1/4 in. diameter probes were clamped to magnetic stands and the signals from the pressure transducers were monitored on a dual channel storage oscilloscope (Tektronix Model 5103N) through the appropriate signal conditioning and amplifier system (Astrodata Model 889). The transducers were placed 5 cm. apart from each other and lightly pressed against the penrose tubing. Pressure waves were induced on the tube with the EM shaker. The signals picked up were stored in the oscilloscope and photographed using a Polaroid Camera mounted on the scope. Figures 1 and 2 show some typical results with signals from top to bottom representing the input signal, the signals from first and second pressure transducers respectively, obtained at a frequency of 100 Hz. The frequency of the signals were varied from 80-120 Hz and we obtained essentially undistorted sinusoidal waves. To determine the wave speed from the continuous signals picked up by the two transducers without purchasing a tone burst generator, the distance between the transducers were varied from 5 to 15 cm. and the signals recorded at the same frequency. The time taken between a reference peak of the signal from the first transducer and the next three consecutive peaks from the second transducer signal were recorded and the corresponding wave speeds computed. For a given fixed distance

a

b

c

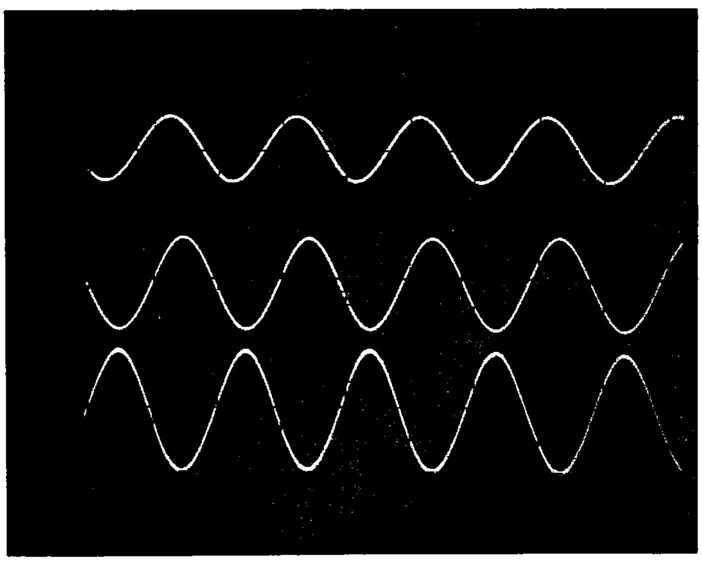

Figure 1. Pressure waves in water filled thin-walled latex rubber tube. a) input signal; b) signal from the first transducer; c) signal from the second transducer. Distance between the transducers = 5 cm. Frequency = 100 Hz.

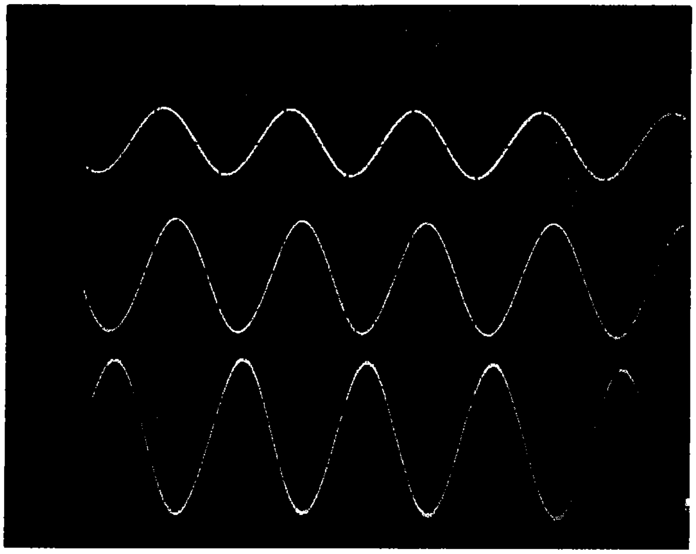

Figure 2. Pressure waves in water filled thin-walled latex rubber tube. a) input signal; b) signal from the first transducer; c) signal from the second transducer. Distance between the transducers = 15 cm. Frequency = 100 Hz.

between the transducers, there was only one consistent value for the wave speed and this value is chosen as the correct wave speed. For the case of water filled penrose rubber tube, the wave speed obtained was 10 m/sec and the value of the Young's modulus computed by the use of Moens-Korteweg relationship, i.e., equation (1), yielded a value of 4.0×10^7 dynes/cm^2. This value is in excellent agreement with that cited in Burton (1971).

The above experiment was repeated by replacing the water with 3% gelatin mix in the tube. The tube was refrigerated for 12 hrs. so that the gelatin was frozen. This gelatin mix has been shown to have similar properties as that of brain material, based on the previous work of our laboratory. A typical result of the experiment with gelatin is shown in Figure 3. This experiment was performed at a frequency of 120 Hz with the two transducers placed 10 cm. apart and a wave speed of 9.09 m/sec was obtained. Various tests with gelatin resulted in the wave speed of the order of 10 m/sec and the results seem to indicate that with either water or gelatin in the tube, the speed of wave propagation tends to agree with the Moens-Korteweg relationship. This relation was hypothesized to be applicable for the spinal cord which consists of the dura mater sheath containing the cerebrospinal fluid in the outer layer and the brain material in the core.

In Vivo Experiments on Dogs

Three dogs were used on the feasibility study with improvements in the experimental technique with each consecutive trial. The first dog was used to establish the surgical procedure as well as to determine what additional surgical instruments and other equipment were necessary

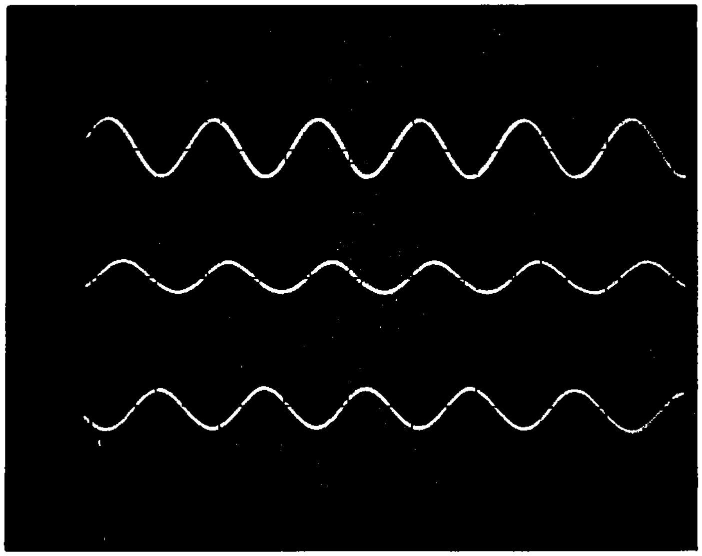

Figure 3. Pressure waves in thin-walled latex rubber tube containing gelatin. a) input signal; b) signal from the first transducer; c) signal from the second transducer. Distance between the transducers = 10 cm. Frequency = 100 Hz.

for the experiment. A medium sized mongrel dog was suitably anesthetized (1 cc diabutal/5 lb weight of the dog) and prepared for surgery. A portion of the spinal cord was exposed in the thoracic region through a posterior approach. The process was very similar to a laminectomy, a standard orthopaedic surgical procedure. After the mechanical experiments on the penrose tube were successfully completed, surgery was performed on another dog in the similar manner. The vibrator probe was pressed against the cord to induce the sinusoidal waves and the two transducers were held by hand to detect the wave motion. As soon as the vibrator was pressed against the cord, there was a reflex jerk on the part of the animal and this prevented us from obtaining any signal from the transducers. Moreover, this jerking motion damaged the silicon diaphragm of the pressure transducers. This difficulty was overcome in the third dog by a local injection of 1 cc of Xylocaine® on the cord just before the experiment was to begin. Xylocaine eliminated the spinal reflex and hence, signals could be picked up on the transducers without any difficulty. The Kulite transducers were replaced by Entran transducers (Model EPA-125E-5), which possessed a stainless steel diaphragm more suitable for this application. The exposed spinal cord of the dog with the shaker and transducers held by hand are shown in Figures 4 and 5, and typical signals obtained in the scope are shown in Figures 6 and 7. Thus, the feasibility of obtaining measurements through wave propagation characteristics on the spinal cord of the dog <u>in vivo</u> have been established. After confirming the feasibility of the <u>in vivo</u> experimental procedure in terms of the pressure wave transmission, a tone burst generator was purchased (General Radio Model 1396B) and the experiments on the latex rubber tube were repeated. Figures 8 and 9 show the input signal as well as the signal from the first and second transducers when

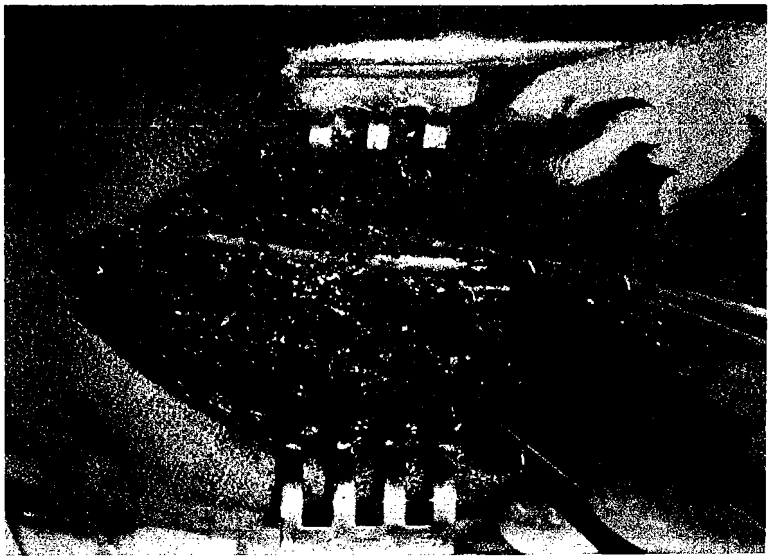

Figure 4. Surgically exposed part of the spinal cord of a dog.

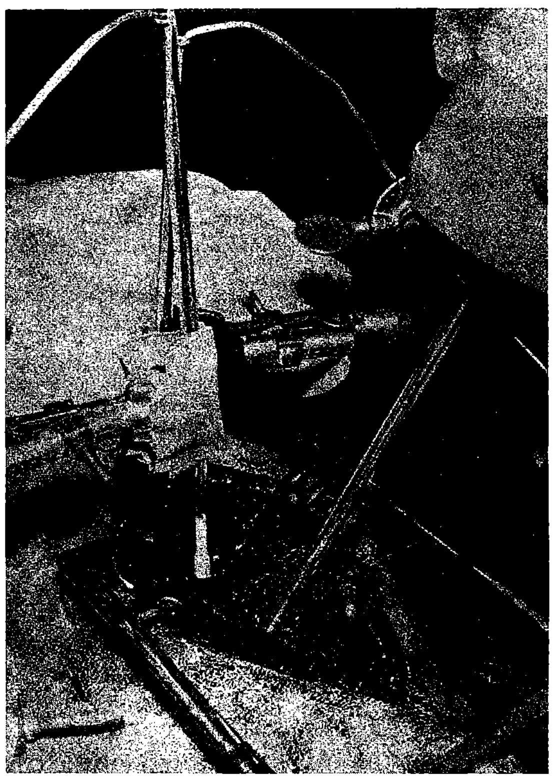

Figure 5. Pressure transducers and the vibrator probe shown along with the exposed spinal cord.

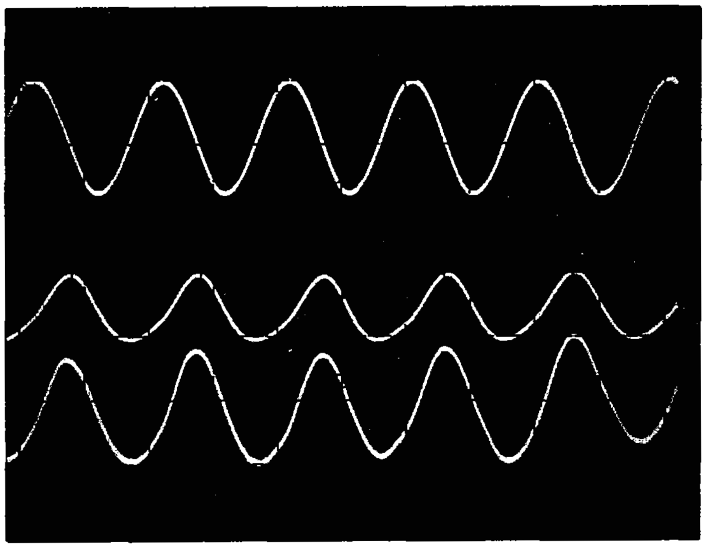

Figure 6. Pressure waves in the spinal cord of a dog. a) input signal; b) signal from the first transducer; c) signal from the second transducer. Distance between the transducers = approximately 2.5 cm. Frequency = 100 Hz.

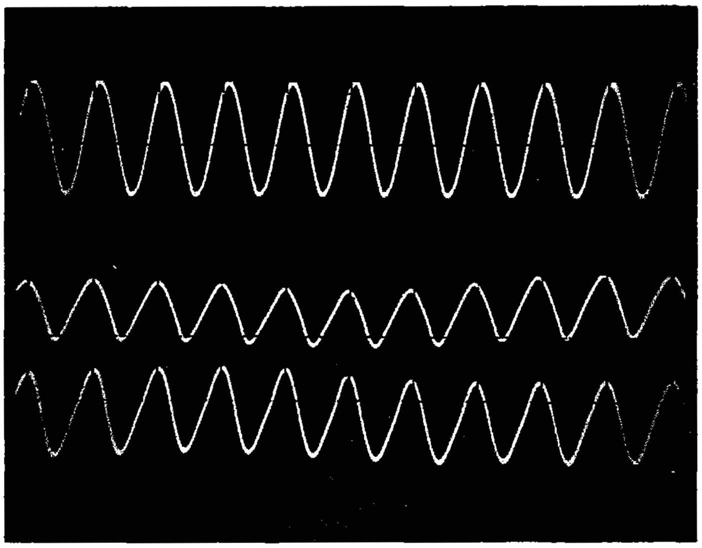

Figure 7. Pressure waves in the spinal cord of a dog. a) input signal; b) signal from the first transducer; c) signal from the second transducer. Distance between the transducers = approximately 2.5 cm. Frequency = 100 Hz.

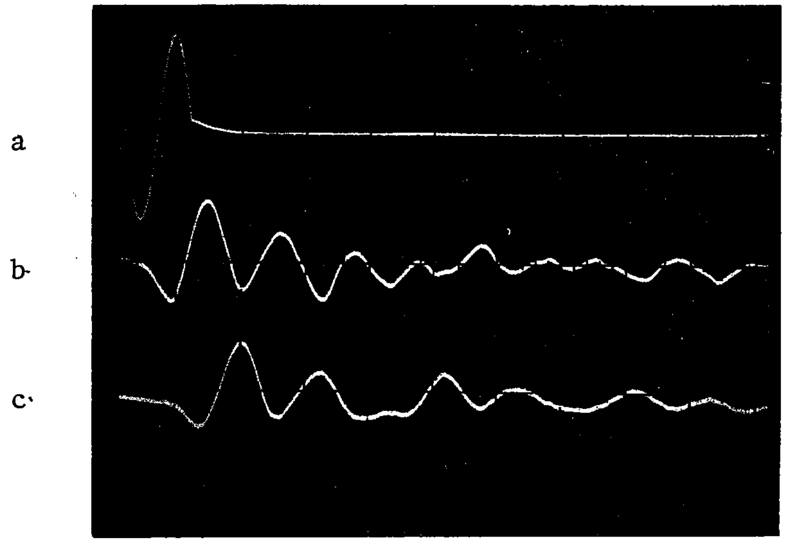

Figure 8. Single wave transmitted in water filled thin-walled latex rubber tube. a) input signal; b) signal from the first transducer; c) signal from the second transducer. Distance between the transducers = 5 cm. Frequency = 100 Hz. Calculated wave speed = 10 m/sec.

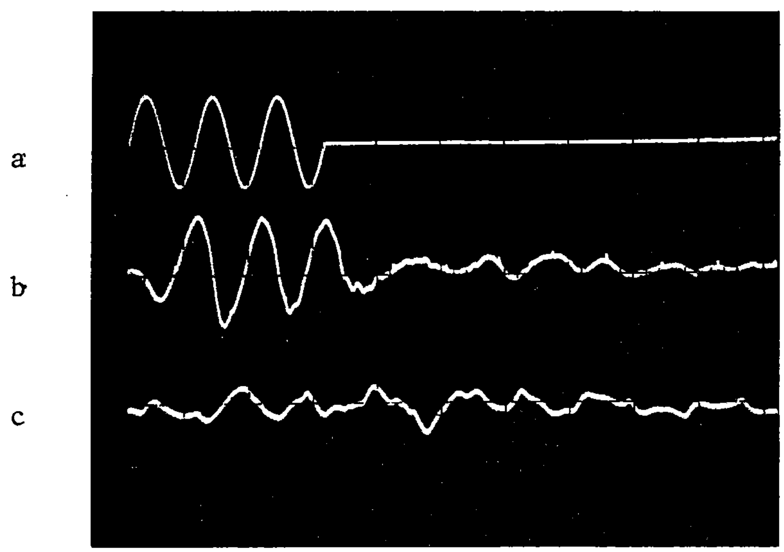

Figure 9. Three wave burst transmitted in water filled thin-walled latex rubber tube. a) input signal; b) signal from the first transducer; c) signal from the second transducer. Distance between the transducers = 5 cm. Frequency = 100 Hz. Calculated wave speed = 10 m/sec.

a single sine wave and a burst of 3 sine waves were used from the tone burst generator. The wave velocity measured from these sets of experiments confirmed the value measured previously by the continuous wave experiments. The tone burst generator proved to be invaluable in following the passage of each wave at the location of the transducers. When the 3 wave train was used, it is evident from Figure 9 that the reflections from the junctions as well as the damping distort the signals picked up by the transducers; but, the peak of the first wave is well defined in the signals from both the transducers and hence, the wave velocity can be measured with reasonable accuracy.

In performing the experiments on dogs, it was learned that a stand should be built to hold the vibrator and the transducers, such that the variations due to manual positioning be eliminated. The in vivo dog experiments were not repeated at this time with the tone burst generator because the ensemble of experiments given above represented the complete success of our feasibility study.

Strain Gage Studies

To determine the feasibility of using strain gages to track the axial and torsional waves, the pressure wave experiments were repeated by replacing strain gages (Micro-Measurement Model EA-06-125AD-120) for the pressure transducers. Using a strain gage mounting kit, strain gages were carefully mounted on the latex rubber tubing and the experiments repeated. Very poor signals were picked up by the strain gages, and even after suitable amplification, the signal to noise ratio was too low for any reasonable data acquisition. The reason for the non-applicability of the strain gages on wave measurements in rubber tubing (and on the dura mater) are believed to be due to the fact that the tubing and the cord has a large compliance compared to the strain gage. The research engineers at the Micro-Measurements Company also agreed with us. (A copy of the letter is available). Moreover, mounting the strain gages on flexible tubing will also stiffen the tubing and hence, change the wave transmission characteristics. This fact was further confirmed when we repeated the measurements with the pressure transducers on the rubber tubing mounted with strain gages. The resulting wave velocity measurements differed from the previously obtained values. Hence, to successfully measure the axial and torsional wave velocity values, two Physitech Electro-optical trackers will be necessary. These trackers were used by Moritz and Anliker (1974) to measure the axial and torsional waves in arteries. The principle of operation for these trackers is to measure optically the motion of a geometrical discontinuity, e.g., a black and white interface, present or attached to the tissue. Two such trackers are necessary for the two locations where the motions are desired. Operation of these instruments in an alternating sweep mode will allow for the simultaneous recording of axial and circumferential displacements of each target for the frequency range of interest.

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